The Identity of the Higgs @ the LHC

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Work collaborated with:
Q.-H. Cao, C.B. Jackson, W.-Y. Keung, J. Lykken, R. Rattazzi, J. Shu, and A. Vichi.

what is the identity of the higgs?

UV identity:

- is the higgs fundamental or composite?
- is the higgs mass fine-tuned?
- is the new physics at the TeV scale, if any, follows from naturalness principle?

IR identity:

- if we observe a scalar resonance, how do we know it has a VEV that breaks the electroweak symmetry?
- what are its quantum numbers and electroweak properties?

all these questions are not necessarily “problems” if we could figure out easily that which one of the 10,000 models gives us the signals at the LHC.

But most likely we need to know these answers <u>before</u> we know for sure which model it is!

in the end of the day, we’d like to reconstruct the lagrangians.

it’s important to start with an open and model-independent mindset!

i will try to provide some partial answers to the above questions, by looking into :

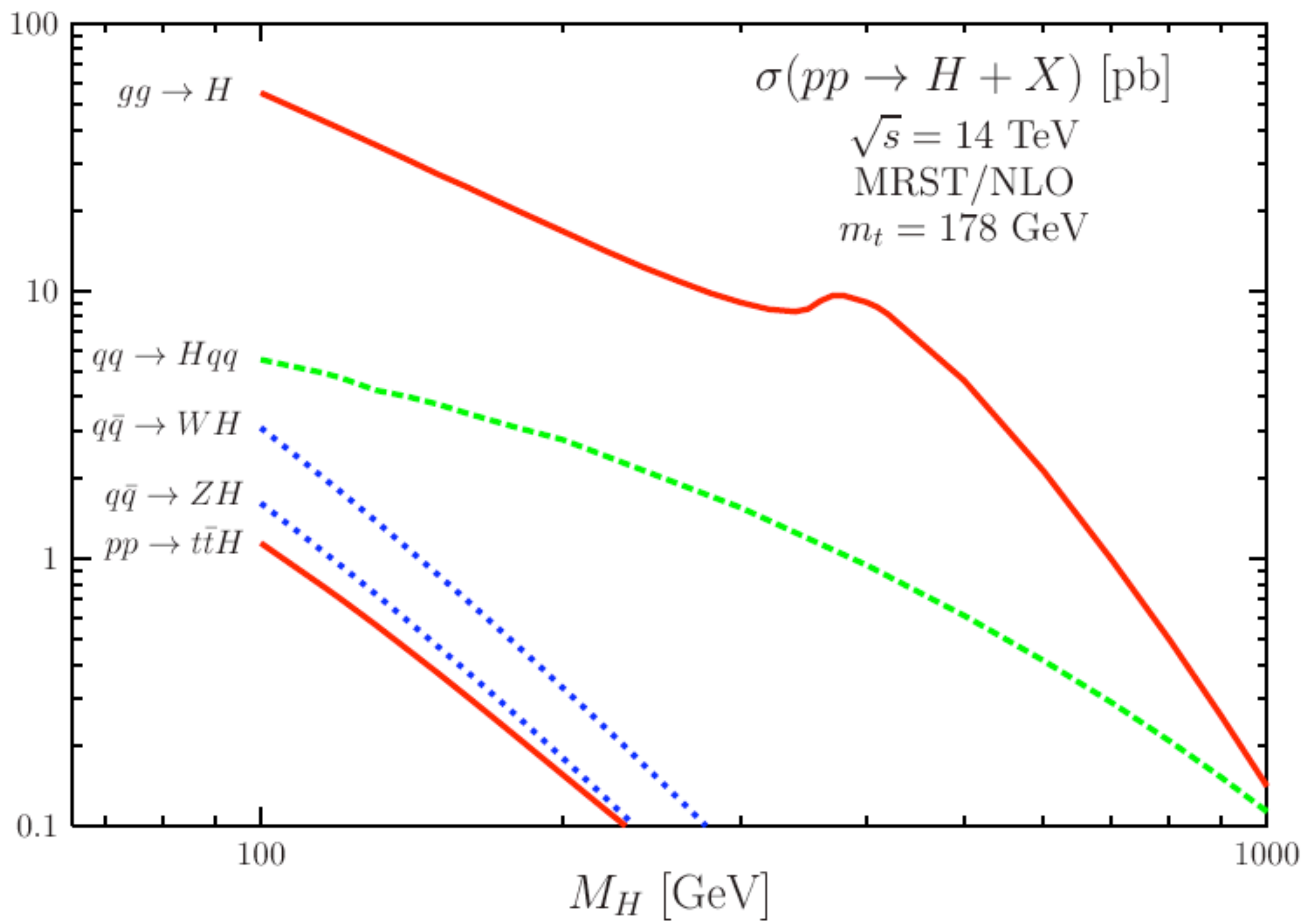
- gluon-fusion production channel:
  compositeness and naturalness
  (I.L., Rattazzi, and Vichi, arXiv:0907.5413)

- decay into ZZ final states:
  spin, CP, and origin of electroweak symmetry breaking
  (Cao, Jackson, Keung, I.L., and Shu arXiv:0911.3398)

- decay branching fractions into pairs of electroweak vector bosons:
  electroweak quantum numbers
  (I.L. and Lykken: arXiv:1005.0872)

compositeness and naturalness

at the LHC gluon fusion is the dominant production channel:

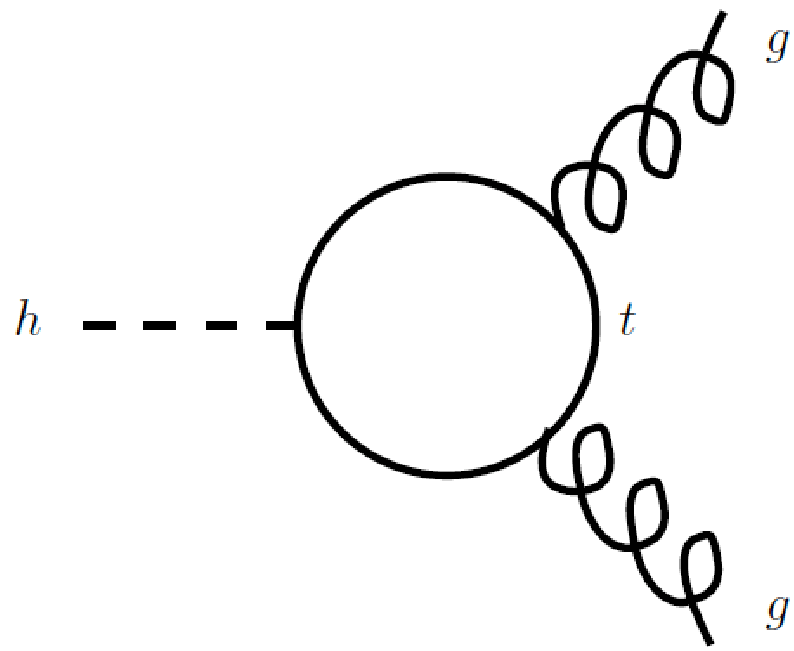


gluon fusion is a loop-induced process!

in the SM the dominant contribution comes from the top loop.

since the top is "heavy", the loop can be shrunk to a point and approximated by a dim-5 operator:

$$\frac{\alpha_s}{6\pi}\frac{y_t}{m_t}\,hG^a_{\mu\nu}G^{a\,\mu\nu} \qquad m_t = \frac{1}{\sqrt{2}}y_t v$$



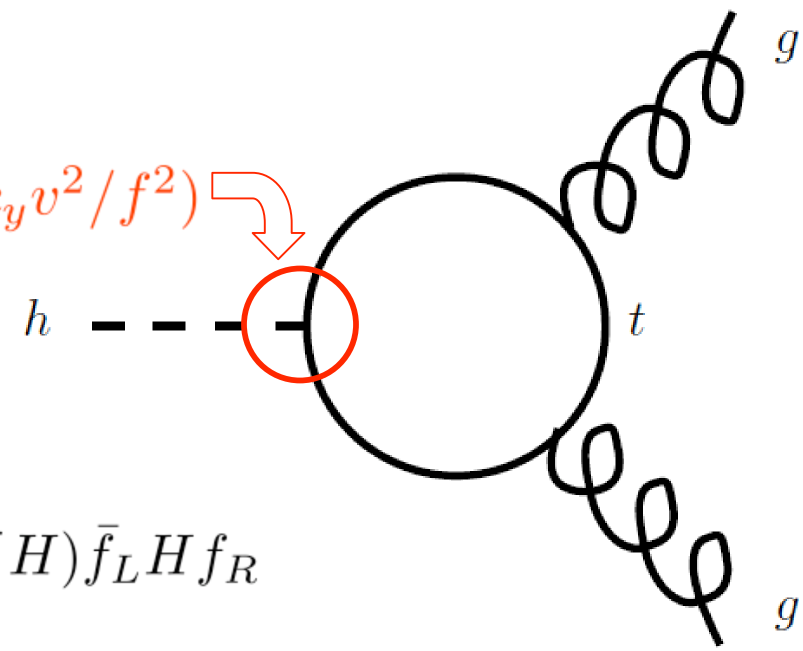
there are three ways new physics could modify the SM cross-section:

1. the higgs-fermion-fermion coupling could be modified:

$$g_{hff} = g_{hff}^{(SM)} \times \left(1 - c_y \frac{v^2}{f^2}\right)$$

$f =$ (roughly) scale of new physics

$g_{hff}^{(SM)}(1 - c_y v^2/f^2)$



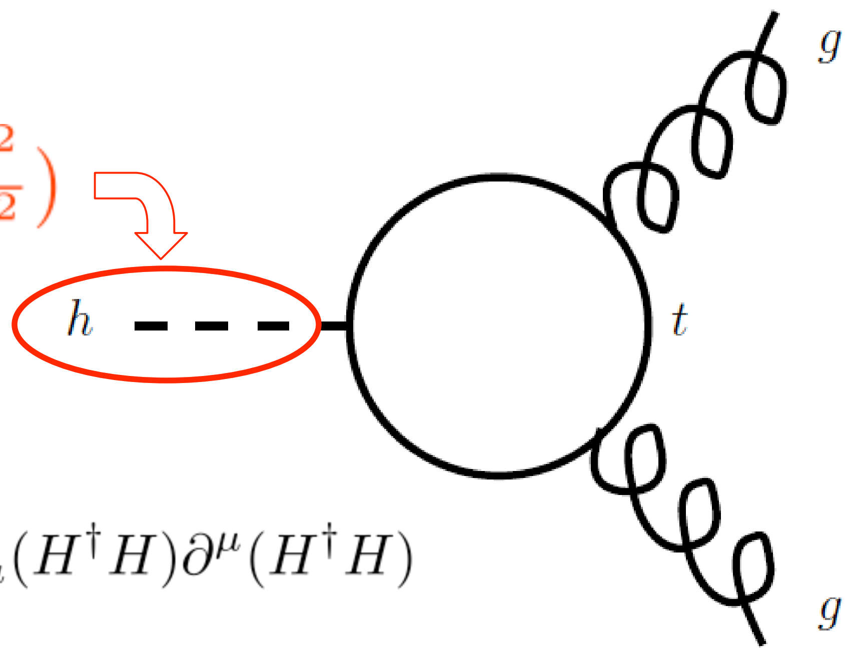
$$c_y \mathcal{O}_y \equiv \frac{c_y\, y_t}{f^2}(H^\dagger H)\bar{f}_L H f_R$$

there are three ways new physics could modify the SM cross-section:

2. the definition of the higgs field may be modified:

$$h \to \frac{h}{\sqrt{1 + c_H v^2/f^2}} \approx h\left(1 - \frac{c_H}{2}\frac{v^2}{f^2}\right)$$

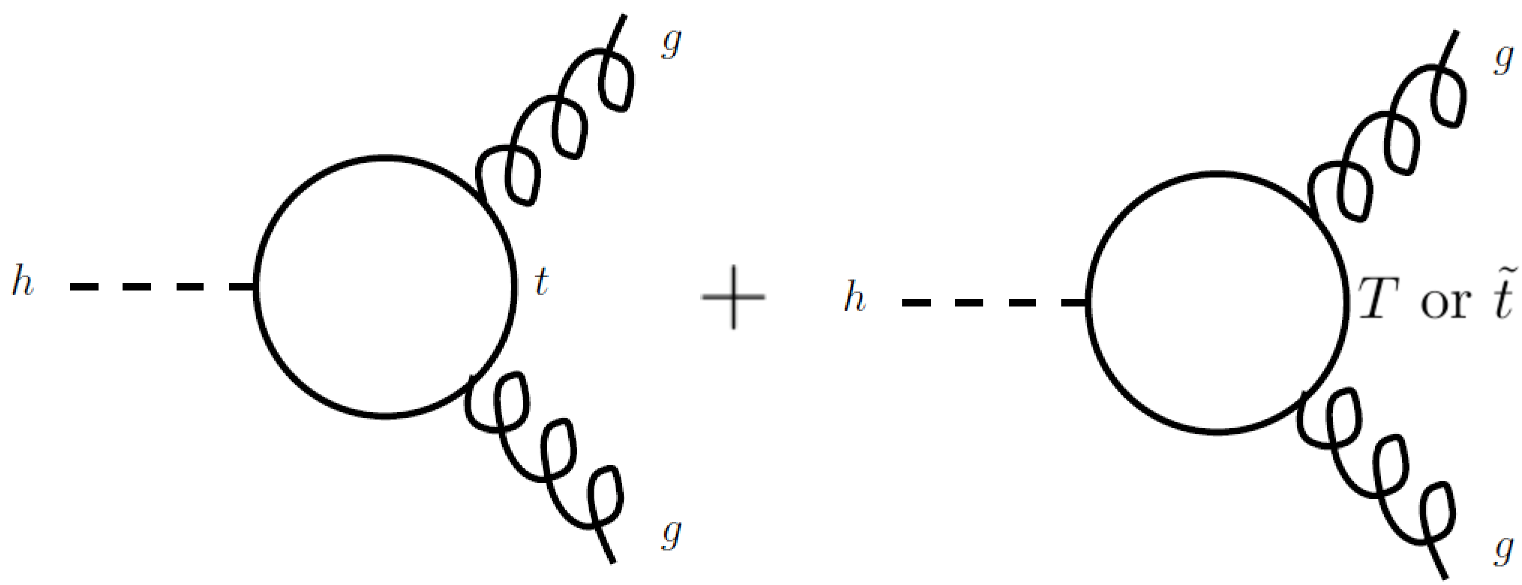
$$h\left(1 - \frac{c_H}{2}\frac{v^2}{f^2}\right)$$



$$c_H \mathcal{O}_H = \frac{c_H}{2f^2}\partial_\mu(H^\dagger H)\partial^\mu(H^\dagger H)$$

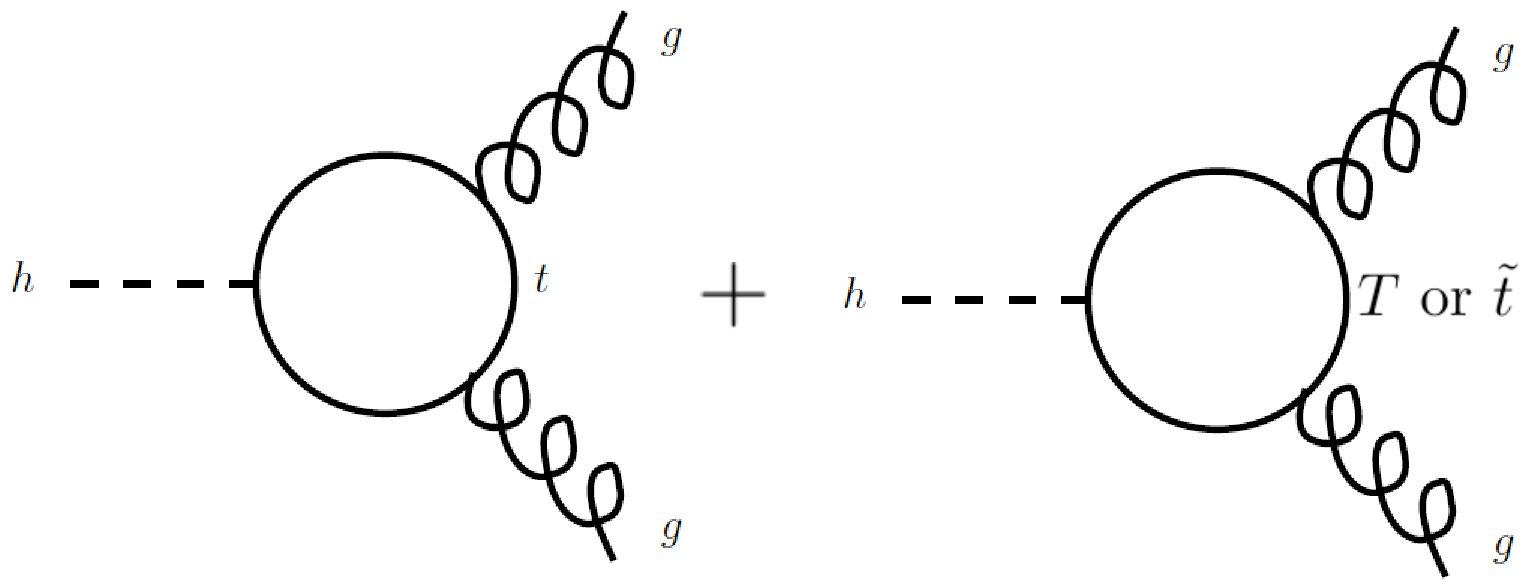
finally, there could a new loop diagram in addition to the SM top loop:

1. for non-supersymmetric theories, it could be a new top-like fermion, the top partner.
2. for supersymmetric theories, it could be a new top-like scalar, the stop.



when the new particle in the loop is heavy, the new contribution is encoded in the parameter c_g:

$$c_g \, \frac{\alpha_s}{2\pi} \, \frac{y_t v}{m_\rho^2} \, h G^a_{\mu\nu} G^{a\,\mu\nu} \qquad\qquad m_\rho = m_T \text{ or } m_{\tilde{t}}$$



summarizing these three effects, we have

$$\xi \equiv \frac{v^2}{f^2}$$

$$\Gamma(h \to gg) \; = \; \Gamma(h \to gg)_{SM} \left[1 - \xi \, \mathrm{Re} \left(c_H + 2c_y + \frac{4y_t^2 c_g}{g_\rho^2 I_g} \right) \right]$$

amazingly, the sign of three parameters all go in the direction of *reducing* the ggh rate for composite Higgs models.

in addition, the interference between SM top and a heavy top-like fermion is *destructive* if the higgs quadratic divergence is *cancelled*, and *constructive* if it is *not cancelled*.

ggh in UED:

the higgs scalar is fundamental and its mass unnatural (fine-tuned).
the rate is enhanced over the SM!

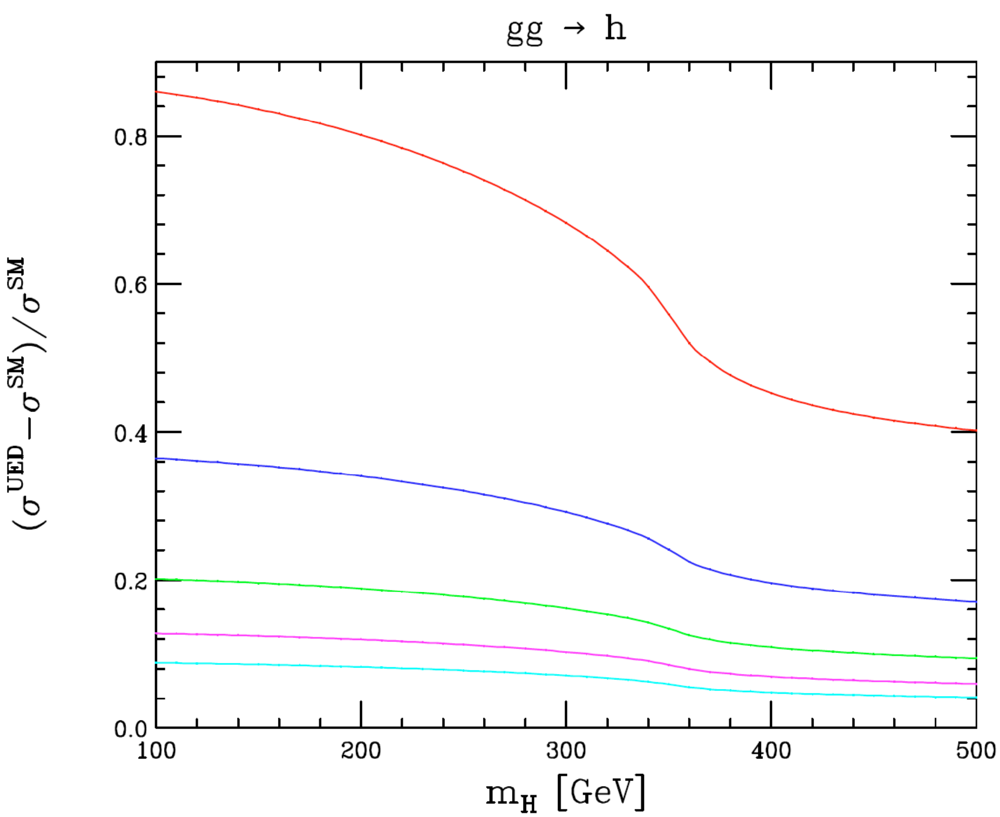
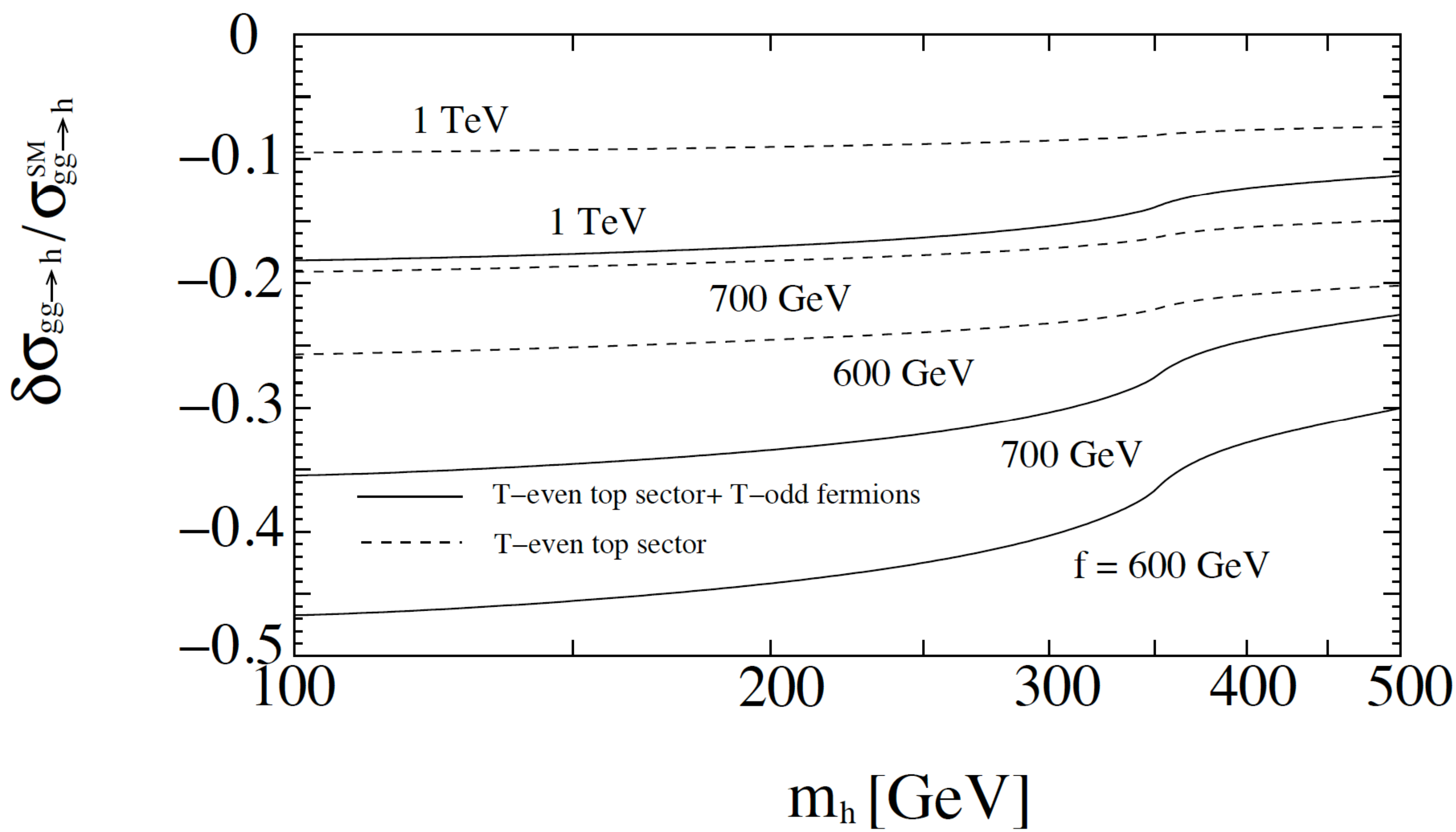


Figure 1: The fractional deviation of the $gg \to h$ production rate in the UED model as a function of m_H; from top to bottom, the results are for $m_1 = 500, 750, 1000, 1250, 1500$ GeV.

F. Petriello, hep-ph/0204067

ggh in the littlest higgs with T-parity (LHT):

the higgs is a composite scalar like the pion and the rate is reduced!



C.-R. Chen et al, hep-ph/0602211

- In the end the ggh rate is a unique handle into the compositeness of the higgs boson as well as the naturalness of its mass.

- composite higgs models generally have a reduced gluon fusion rate.

- unnatural models tend to have an enhanced production rate.

so this is an important number to measure precisely!

spin, CP, and higgs mechanism

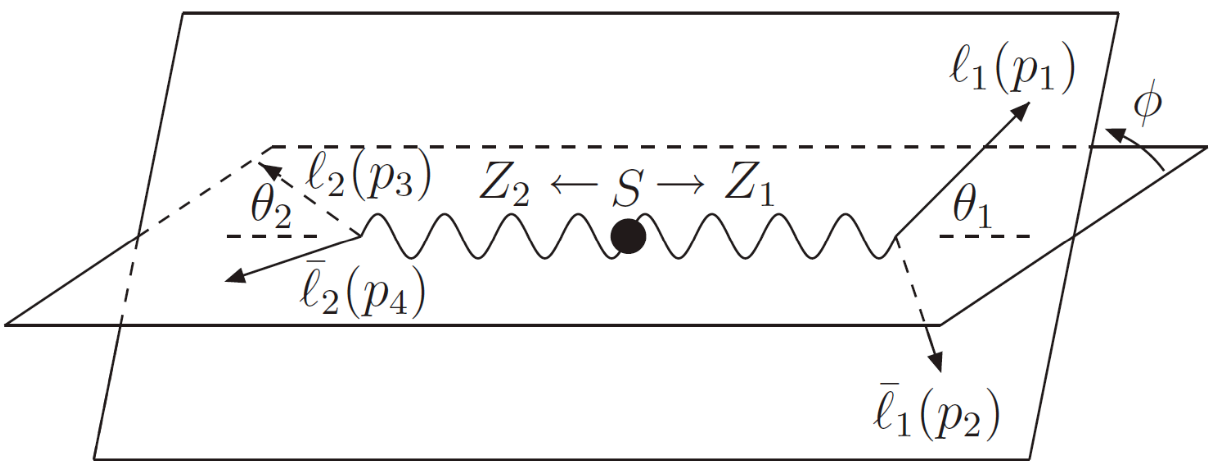
higgs -> ZZ ->4l is the gold-plated mode for higgs mass~>145 GeV.

- There have been studies using the angular correlations to determine the spin and CP property of the resonance (eg, see the CMS TDR.)

I wish to emphasize the usefulness of two observables:

a) the total width

b) ϕ, the azimuthal angle between the two decay planes of the Z.



a general analysis of a scalar decaying into ZZ:

- the higgs mechanism predicts

$$|D_\mu H|^2 = \left| \left(\partial_\mu - ig \frac{\sigma^a}{2} W_\mu^a - ig' \frac{1}{2} B_\mu \right) H \right|^2$$

$$\Rightarrow \quad \left(1 + \frac{h}{v}\right)^2 m_V^2 V_\mu V^\mu \qquad g_{hVV} = -2i \frac{m_V^2}{v} g_{\mu\nu}$$

- but there are still two other possible couplings of a scalar with two Z bosons:

the other two terms are higgs look-alikes!!

$$\mathcal{L}_{eff} = \frac{1}{2} m_S\, S \left(c_1 Z^\nu Z_\nu + \frac{1}{2} \frac{c_2}{m_S^2} Z^{\mu\nu} Z_{\mu\nu} + \frac{1}{4} \frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

higgs mechanism predicts only this term!

- we computed the azimuthal angular distribution, assuming new physics could be integrated out:

Negligible (~0.06) in the SM!

$$\frac{d\Gamma}{\Gamma d\phi} = \frac{1}{N}\left\{\frac{8}{9}\cos(2\phi+2\delta) + \frac{\pi^2}{2}\frac{M_L}{M_T}\left(\frac{g_R^2-g_L^2}{g_R^2+g_L^2}\right)^2\cos(\phi+\delta) + \frac{16}{9}\left(\frac{M_L^2}{M_T^2}+2\right)\right\}.$$

$\delta = 0$ for vanishing c_3. (CP-even scalar!)

$\delta = \pi/2$ for vanishing c_1 and c_2. (CP-odd scalar!)

- previous studies (eg, CMS TDR) only focus on c_1 and c_3 without including c_2!

we see the cos(2ϕ) dependence, signaling a spin-0 resonance.
notice the cos(ϕ) component is tiny!
(for spin-1 resonance it would be cos(ϕ).)

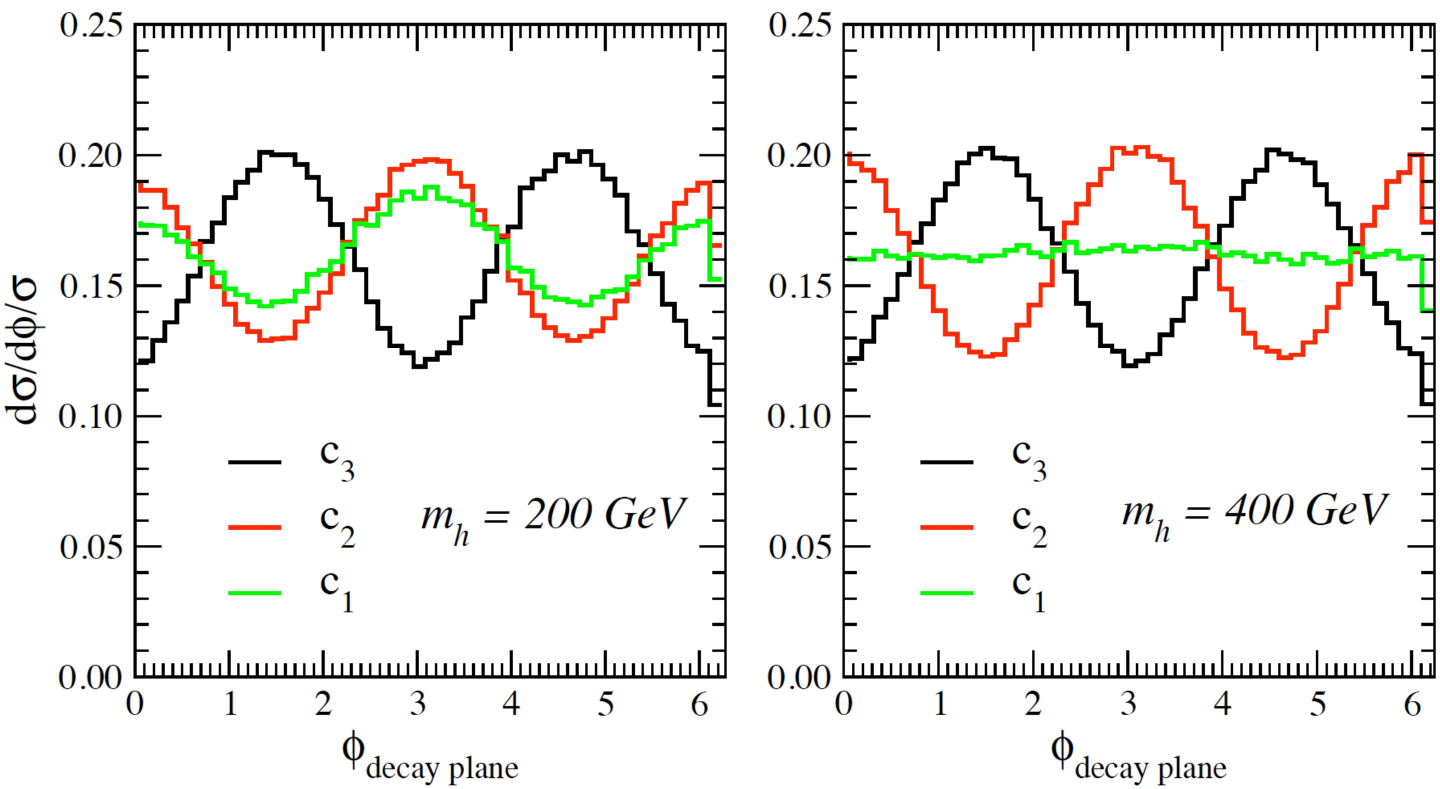


FIG. 4: *The normalized azimuthal angular distributions for 200 and 400 GeV scalar masses, turning on one operator at a time.*

notice c_1 and c_2 will be difficult to tell unless the higgs is heavy!

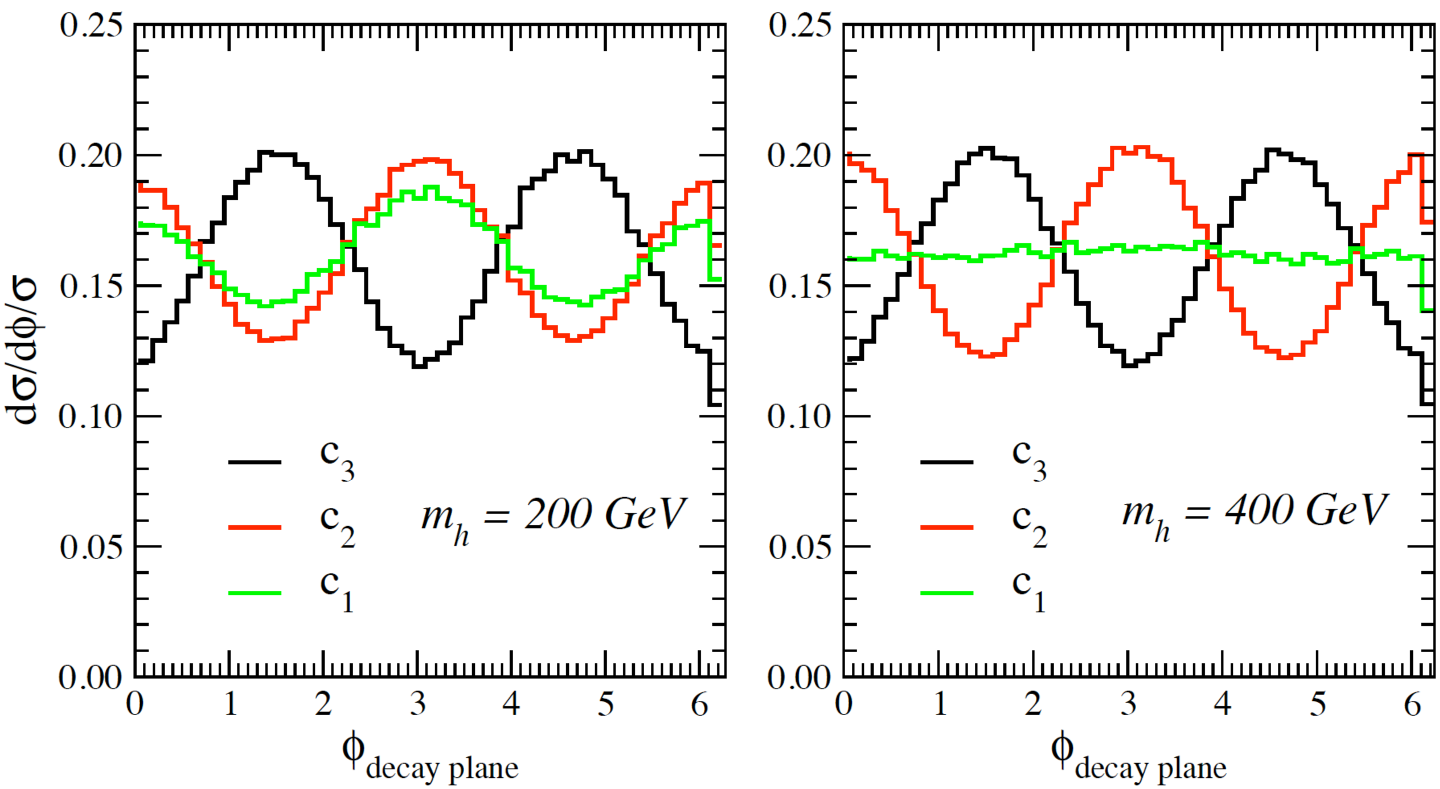


FIG. 4: *The normalized azimuthal angular distributions for 200 and 400 GeV scalar masses, turning on one operator at a time.*

- another handle makes use of the crucial observation that the two non-Higgs operators

$$S \times \left(\frac{1}{2} \frac{c_2}{m_S^2} Z_{\mu\nu} Z^{\mu\nu} + \frac{1}{4} \frac{c_3}{m_S^2} \epsilon_{\mu\nu\rho\sigma} Z^{\mu\nu} Z^{\rho\sigma} \right)$$

are both loop-induced:

$$c_2 \sim \mathcal{O}\left(\frac{1}{16\pi^2} \right) \qquad c_3 \sim \mathcal{O}\left(\frac{1}{16\pi^2} \right)$$

recall that the gluon fusion production of the higgs, $h\, G^a_{\mu\nu} G^{a\,\mu\nu}$,is also loop-induced!

- for a higgs look-alike to decay through either one of the coupling, the partial width is also loop-induced:

$$\Gamma(S \to ZZ) \approx \text{loop-induced for both } c_2 \text{ and } c_3$$

- thus in order to have a sizable branching ratio, the total width must be also loop-induced and order-of-magnitude smaller than that of the SM Higgs:

$$\Gamma_{total} \ll \Gamma_{total}^{(SM)}$$

otherwise we simply would not observe the resonance in the ZZ channel in the early running!!

a higgs look-alike would have a very narrow width, which is buried under the energy resolution of the detector!

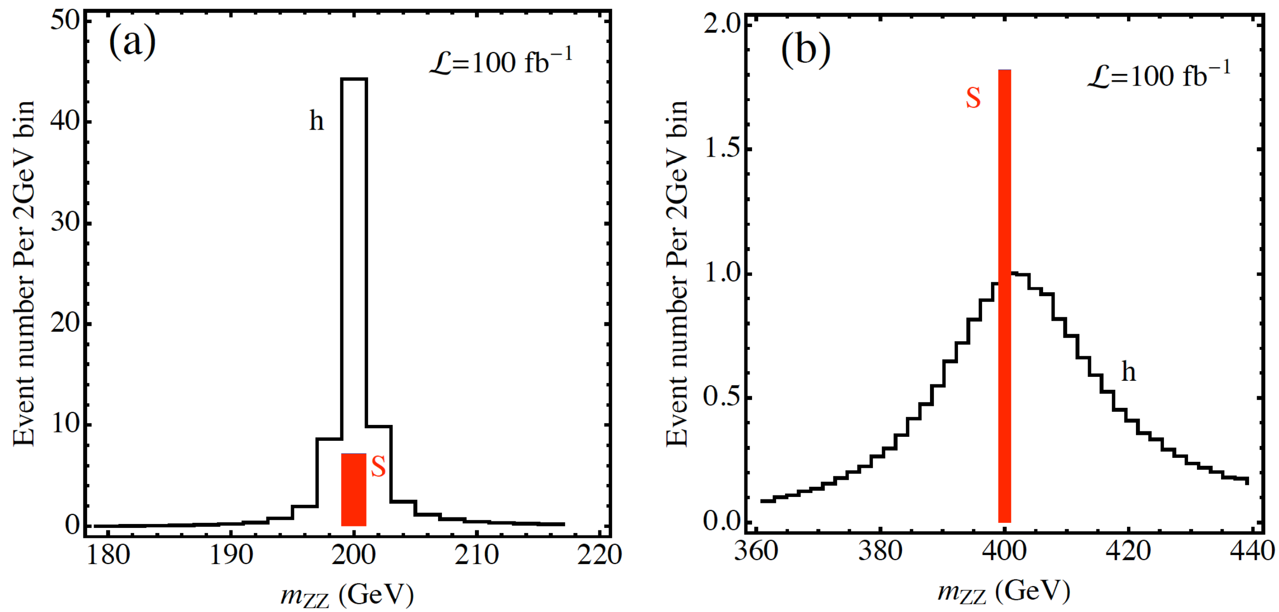


FIG. 3: *The ZZ invariant mass distribution for a SM Higgs boson and a scalar S decaying through loop-induced effects, using a 2 GeV bin size. The narrow width of S is below the detector resolution, resulting in a concentration of all events in just one bin. In the plot we assume the event rate of $gg \to S \to ZZ \to 4\ell$ is only 10% of rate for the SM Higgs boson.*

- if a resonance is observed in the ZZ final states, the azimuthal angular distribution would provide crucial information on the spin and CP property of the resonance.

- the width of the resonance provides a smoking-gun signal on the higgs nature (or the lack thereof) of the resonance .

electroweak properties

- electroweak quantum numbers determine its couplings to pairs of electroweak vector bosons:
  WW, ZZ, $Z\gamma$, and $\gamma\,\gamma$.
- empirically the rho parameter is measured to be very close to unity, at the percent level.
- rho=1 can be guaranteed by the custodial symmetry, an accidental global symmetry of the scalar sector of the SM after EWSB.

- more specifically, after EWSB:

$$SU(2)_L \times SU(2)_R \to SU(2)_C$$

- an electroweak doublet transforms as

$$(\mathbf{2}_L, \mathbf{2}_R) = \mathbf{1} \oplus \mathbf{3}$$

the singlet is the neutral component receiving a VEV!

- In order to preserve the custodial symmetry, only a custodial singlet can receive a VEV!

scalars must furnish a (N_L, N_R) representation!!

- remarkably, only a custodial singlet and a 5-plet can have non-vanishing couplings to pairs of electroweak vector bosons!

- The singlet case includes two possibilities:
  a) dim-4 operator (electroweak non-singlet)
  b) dim-5 operator (electroweak singlet)

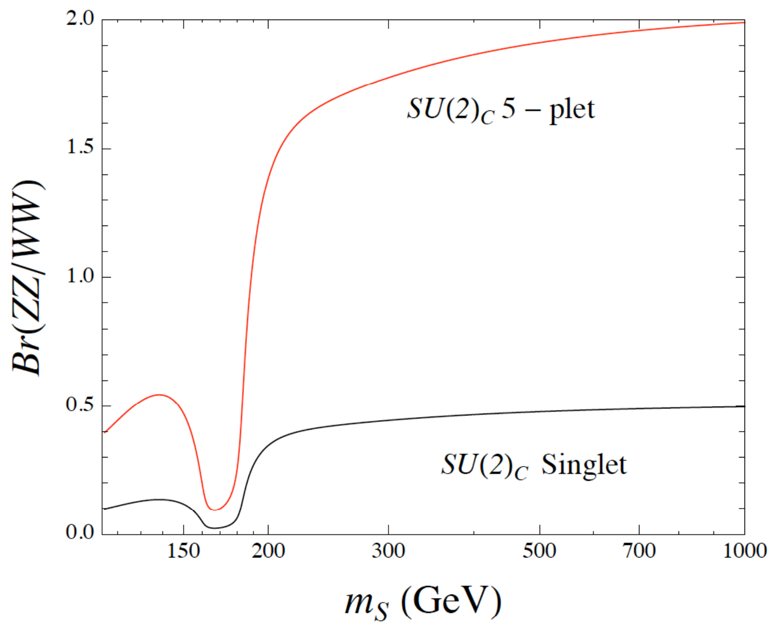


FIG. 1: *Ratio of branching fractions into WW and ZZ, $Br(ZZ/WW)$, for an $SU(2)_C$ singlet and a 5-plet, as a function of the scalar mass.*

An amusing example:

m_S (GeV)	$Br(\gamma\gamma/WW)$	$Br(ZZ/WW)$	$Br(Z\gamma/WW)$
115	2.7×10^{-2} (2.7×10^{-2})	5.1×10^{-2} (0.11)	39 (9.0×10^{-3})
120	1.7×10^{-2} (1.7×10^{-2})	5.7×10^{-2} (0.11)	35 (8.2×10^{-3})
130	7.8×10^{-3} (7.8×10^{-3})	6.7×10^{-2} (0.13)	26 (6.7×10^{-3})
140	4.0×10^{-3} (4.0×10^{-3})	7.1×10^{-2} (0.14)	18 (5.1×10^{-3})
150	2.0×10^{-3} (2.0×10^{-3})	6.4×10^{-2} (0.12)	10 (3.5×10^{-3})
170	1.6×10^{-4} (1.6×10^{-4})	1.4×10^{-2} (2.3×10^{-2})	0.81 (4.1×10^{-4})

TABLE II: *Ratios of branching fractions for an electroweak singlet scalar when $Br(\gamma\gamma/WW)$ is tuned to the SM value. The value in the parenthesis is for the corresponding SM prediction.*

while the $Z\gamma$ channel is significantly enhanced.

It is extremely important to measure all four decay modes into WW, ZZ, Zγ, and $\gamma\ \gamma$!!

- a higgs imposter could be revealed by measuring all four decay modes.

- if observe multiple scalars, only one non-trivial mixing scenario need to be considered ---- have enough measurements to disentangle the mixing in principle.

- using vector boson fusion one could also determine the number N in the (N_L, N_R) representation.

$$\boxed{g_{h_1^0 WW} = g_{h_1^0 ZZ}\, c_w^2 = \sqrt{\frac{N^2-1}{3}}\, g m_W}$$

Conclusion

- The gluon fusion production rate is a unique handle into the compositeness of the Higgs boson as well as the naturalness of the mass.
- If a scalar resonance is observed in the ZZ final states, the azimuthal angular distribution would provide crucial information on the spin and CP property of the resonance.
- The width of the resonance provides a smoking-gun signal on the Higgs nature of the resonance.
- Once a scalar is discovered, it'll be important to have a correlated understanding of decays into all four pairs of electroweak vector bosons!